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A Tour of the Universe

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You are all astronauts on this spaceship - the Earth, a lump of rock covered with a thin scum of water, moss and air that makes up the world we know. Life on Earth is intimately tied to the Universe through which it travels. Most directly, it is influenced by the Sun. We depend on the Sun for our existence - our heat and light and almost all our energy sources come ultimately from the Sun. But the Sun can also be dangerous - we are protected from its full fury by the atmosphere, which screens out ultraviolet and x-ray radiation, and by the magnetosphere, which catches subatomic particles thrown at us by the Sun and bounces them away or funnels them down on the poles to hit the atmosphere and make the beautiful aurorae that those of you from northern latitudes may have seen.

We often think of the Earth as stopping a few miles over our heads, then there's this big gap of vacuum till you get to some other planet or star, but that's not really so. You go up a couple thousand miles, what you get is pretty good vacuum by lab standards, but there's a tiny amount of gas still present, a little bit of magnetic field, the odd relativistic particle. Who cares? Well, space is big, and if you take a huge region, like 100 times the volume of the earth, you still scoop up a fair bit of gas. So it turns out that even really tiny densities of stuff can be important. And this idea carries on throughout our study of astrophysics; there's a boundary between the gas asscoiated with the Earth and the gas that's coming from the Sun, and further out the gas coming from the sun hits the even thinner gas that lies between all the stars, and so on. So actually the Earth is touching the Sun and the Sun and the other stars are touching, they're immersed in this stuff that's so thin its ridiculous, but it plays a key part in the story I want to tell.

I want to talk mostly about the stars, but because some of you are new to astronomy I want to give a bit of context first. Your ideas of what planets are like come from living on one, first, and second, on watching Star Trek. They're like round, made of rock or something similar, usually covered in some kind of air. Right? Well, not necessarily. That's one kind of planet, the rocky worlds, like Earth, and Venus - Venus is covered with clouds of sulfuric acid, its surface temperature is enough to make rock glow red, there's so much carbon dioxide atmosphere that it crushed the first 4 spaceprobes to land there. Otherwise it's just like home. It's by studying Venus that scientists started paying attention to the chance that a similar thing might happen to the Earth if we mess with its atmosphere too much.

Mars is another rocky world, here you see a shot of a volcano that's bigger than New England. Mars has a really thin atmosphere, and its really cold, but there's lots of water locked up in the rocks, so itd be an interesting place to go visit.

But there are really different kinds of planet, and really the generic planet is probably more like Jupiter. Jupiter's a gas giant, it has no solid surface, mainly a huge ball of liquid hydrogen. The Great Red Spot is a storm system that's been around for centuries, its twice as big as the Earth. The small objects are moons of Jupiter that are decent sized worlds in their own right. Saturn is another gas giant; the rings are millions of lumps of ice orbiting the planet. Neptune is another. There's a third kind of world, which we only got to see during the Voyager exploration of the outer solar system: the ice worlds, like Iapetus, which is kind of a snowball several hundred miles across. Geologists are only just starting to work out the sorts of processes that happen on a world like this.

All the planets we know are orbiting a single star - the Sun. Now we're jumping up in scale. The Sun is a million miles across, it's a sphere of ionized gas. It's a star; the nearest star; our star. The fact that it's so much brighter than the other stars tells you right away that the others are much further away. To give you an idea of the scale to the nearest stars, Voyager took 12 years to get from Earth to Neptune. It'll pass close to some of the nearer stars in about 50 000 years. Now this brings us to the fact that astrophysicists like me are snobs. For centuries astronomy was mostly about the planets, because we didnt know much about the stars. Now we can send a robot to Mars and have it grab a handful of soil and taste it, we tend to say 'Oh, that's just planetary science now, it's too easy to be called astronomy'. The stars (apart from the Sun) are still far beyond the reach of our space probes, so we have to do the best we can by looking at them from a distance.

Well, you'd think that wouldnt be a lot of use, but there's an amazing trick that opens up the universe to us. That trick is the spectral line. Pass light through a prism and you split it up into a spectrum. You can measure how much of each color is mixed in the light. Now we heat up a gas made of iron atoms till it glows. Pass that light through a prism and you get these lines. They're in a particular pattern, always the same pattern for iron at the same temperature and density. Another element, like hydrogen, will have a different pattern. Each element has its own fingerprint. Now you probably know that these lines are because of the electronic structure of the atoms; the electrons jump from one energy level to another and give off the surplus energy as a light photon of a very precise color. Color is just related to the energy of the light particles. But at the turn of the century astronomers didnt know this - and they didnt need to. They just needed to know that if you pass the light from a star through a prism and see this pattern, the atmosphere of that star has iron in it. So you can see what the stars are made of from light years away.

In the early part of the century the Harvard astronomer Annie Cannon carried out the first large-scale classification of the spectra of stars. She grouped them into types which we now know represent stars of particular temperature. Thus, our sun has a G type spectrum in her system; this is because its surface temperature is about 5000 K. Cannon classified a quarter of a million stars in this way. The system was extended by another Harvard astronomer, Antonia Maury, who subdivided the types into classes depending on the exact form of the spectral lines; it turns out that this distinction is due to the size of the star. Our star is a class GV, meaning it is a yellow dwarf star. A million miles across may not sound very dwarf to you, but you should see what a supergiant is like.

Once lab spectra were better understood, it was possible to use the spectra to work out what the composition of the star was. Probably the landmark in this field was Cecilia Payne's PhD thesis in the 1920's in which she showed that the stars were made up mostly of hydrogen gas. This was so unexpected that she added a note saying that there must be something wrong with the physics! The discovery that hydrogen was by far the most common element in the universe was a Big Clue. Combined with the work of Arthur Eddington in England on the internal structure of stars, astronomers realized that a star is just a big nuclear fusion reactor for burning hydrogen into heavier elements.

What happens when you have a big cloud of gas in space? Its own gravity wants to drag it together into a big ball. But as you squeeze gas, you heat it (Boyle's law) - the pressure increases and it resists collapse. Let's balance gravity and pressure:

Stars and the Jeans mass

Each atom has gravitational energy $GMm/R = \frac{4}{3}\pi G\rho m R^2$. If the atoms were far enough apart not to hit each other, they would all fall to the center of the cloud, converting their gravitational energy into kinetic energy.

$$\frac{1}{2}mv^2 \sim mG\rho R^2$$

so

$$t_{fall} = \frac{R}{v} = \frac{1}{\sqrt{G\rho}}$$

But instead the atoms will collide, acting as an ideal gas, in which each particle has thermal energy of order kT.

$$\frac{E_{grav}}{E_{therm}} \sim \frac{G\rho m R^2}{kT} = \frac{R^2}{kT/t_{fall}^2}$$

so for a gas cloud of given density and temperature, gravitational collapse is stopped by the gas pressure if its size is smaller than

$$R_J = \frac{\sqrt{kT}}{t_{fall}}$$

Star lifetimes

The cloud then slowly shrinks as it gets hotter and denser in the middle. This is regulated by the rate at which energy can leak out from the gas cloud. A star is a gas cloud where gas pressure balances gravity and the core has become hot enough for nuclear fusion to occur.

Nuclear fusion can turn 0.7 per cent of the rest mass of its fuel into energy. The sun turns 10^{14} tonnes of matter into energy each year; that's 10^{-13} of its mass. At this rate it will burn up its fuel in 100 billion years. (Actually only a tenth the fuel is available).

The Eddington Limit

Star puts out an amount of energy L each second in the form of light photons each of energy kT and momentum kT/c. So there are

$$\frac{L}{4kT\pi R^2} \text{ photons/s/unit area}$$

emitted from the surface. These like to hit atoms of cross-section σ pushing each atom out with momentum

$$\frac{L\sigma}{4\pi R^2 c}$$

each second.

So in addition to the outward pressure of the gas, the light escaping from the star pushes on the outer layers. Balancing this pressure with gravity

$$\frac{L\sigma}{4\pi R^2 c} = \frac{GMm}{R^2}$$

we derive

$$L = \left(\frac{4\pi G m c}{\sigma}\right) M$$

If the luminosity is bigger than this, the Eddington luminosity, the star will be disrupted and the outer layers will blow off. Our sun is 30000 times too feeble to be in danger of doing this.

Galaxies

A typical galaxy contains 10^{11} stars, mostly smaller than the sun. Our sun is 30000 lightyears from the center of the galaxy, so equating orbital KE and PE we expect that its orbital speed will be

$$V = \sqrt{GM_{gal}(\text{within 30 kly})/R}$$

and it will orbit the galaxy in

$$T = (R/V) = \sqrt{R^3/GM_{gal}} \sim 10^8\text{yr}$$

We would expect that the speed of stars in the outer parts of galaxies would be slower. But instead for most galaxies the orbital speeds stay the same, implying that the further out you go the more mass you find. Since the galaxy doesnt put out much light in the outer regions, this has led to the idea that most of the matter in the galaxy is an unknown, dark component

Quasars

Some galaxies contain a bright source of radiation in their cores: quasars.

Quasars can be up to a thousand times as bright as the galaxy they are in. They have

$$L = \text{mass of 1 whole star} \times c^2 \text{ per year}$$

From variability arguments

$$R < 1 \text{ light year}$$

Eddington argument requires huge mass:
10^8 solar masses?